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PUBLICATION
A.V. Boris *et al.*, "Josephson Plasma Resonance and Phonon Anomalies in Trilayer $Bi_2Sr_2Ca_2Cu_3O_{10}$", Physical Review Letters, **89**, 277001 (2002).

FUNDING
Max Planck Institute for Solid State Research,Partially by Alexander von Humboldt Foundation and Ministry of Education of Czech Republic

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Superconductivity Induced Electronic Excitation and Phonon Anomalies in Trilayer $Bi_2Sr_2Ca_2Cu_3O_{10}$

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Charge and lattice dynamics along c axis perpendicular to the CuO_2 superconducting (SC) planes have been studied in a Bi2223 crystal by infrared ellipsometry using synchrotron radiation. The far-infrared (FIR) conductivity data reveal that a strong absorption band corresponding to a transverse Josephson plasmon develops as the crystal enters the SC state. The related effect of the FIR spectral weight increase is directly opposite the spectral weight decrease observed in conventional SC's. This unusual effect highlights that an anomalously large energy scale beyond the FIR range can be attributed to formation of the SC condensate in high-T_c superconductors. We also observe phonon anomalies, which suggest that the Josephson currents lead to a drastic variation of the local electric field within the block of closely spaced CuO_2 planes.

The transition from a normal metal to a superconductor (SC) below the critical temperature, T_c, is accompanied by a redistribution of spectral weight (*SW*) for the real part of the complex optical conductivity, $\sigma(\omega)$, from finite frequencies in the normal state (NS) into a δ-function at zero frequency in the SC state that represents the loss-free response of the SC condensate. For classical SC's, the energy gap determines the relevant frequency range over which the *SW* of the δ-function is collected, so that noticeable changes occur only for $\omega < 6\Delta$ (Ferrell-Glover-Tinkham (FGT) sum rule). Recently, it was found that the FGT sum rule is partially violated for the *c* axis response of some of the high-T_c cuprate compounds: the *SW* loss in the FIR below T_c is smaller than the *SW* of the δ-function at zero frequency. The change of the FIR-*SW* in the SC state is small and hard to measure experimentally. Nevertheless, due to its important implications, the reports on the FGT sum rule violation have attracted considerable attention. It implies that a very large frequency scale is involved in the SC pairing and seems to rule out any conventional mechanism that relies exclusively on low-frequency bosons like phonons. Instead, it supports models where a decrease in the *c* axis kinetic energy below T_c provides a significant contribution to the SC condensation energy.

Alexander Boris at NSLS beamline U4IR.

These far reaching implications call for further experiments on a compound where the related *SW* transfer is larger and therefore more easily identified. The most promising candidates are multilayer high-T_c compounds, which contain more than two CuO_2 plane per unit cell. Here we present ellipsometric data of the *c* axis dielectric response of the trilayer compound $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223). The *ellipsometric measurements* have been performed at the infrared beamlines of the synchrotron radiation sources at ANKA in Karlsruhe, Germany and at NSLS in Brookhaven. The high brilliance of the synchrotron enables us to obtain accurate data in the FIR spectral range even on mm-sized samples.

Figure 1 shows the real part σ_1 of the *c* axis optical conductivity of Bi2223 at the three different doping levels. The NS spectra are dominated by the contributions of

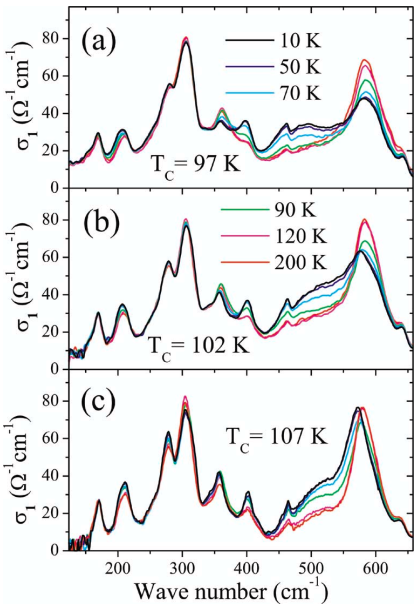

Figure 1. *Real part, $\sigma_1(\omega)$, of the FIR c axis conductivity of Bi2223.*

several IR-active phonons, the one of the charge carriers is extremely weak. In the NS the spectra exhibit hardly any noticeable changes. Right below T_c, however, the spectra change appreciably. The most prominent feature is the broad absorption band around 500 cm^{-1}, which appears below T_c and grows rapidly with decreasing temperature. The center of this band shifts towards higher frequencies with increasing doping. A similar absorption band has been previously identified in the bilayer compounds $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$ where it has been attributed to a transverse Josephson-plasma resonance (t-JPR). This can be understood in terms of the interlayer-tunneling model, which assumes that the CuO_2 planes are weakly coupled by the Josephson currents in the SC state. For bi- or trilayer compounds, this results in two kinds of Josephson junctions (Josephson superlattice) with different longitudinal plasma frequencies. Their out-of-phase oscillation gives rise to the t-JPR, which has been assigned to the absorption peak that develops below T_c. The *SW* of this feature is very large and gives rise to a considerable increase in the FIR-*SW* below T_c. Such an apparent increase in the *SW* is certainly not expected for any conventional SC where the FIR-*SW* should be removed and transferred to the δ-function at zero frequency (**Figure 2a**). **Figure 2b** shows a sketch of the SC induced change of the FIR conductivity in Bi2223. The data represent a striking manifestation of the violation of the FGT sum rule. They highlight that a significant amount of *SW* is transferred from higher frequencies to the absorption band near 500 cm^{-1}. This result is independent of a particular model that is used to explain the origin of the band. We emphasize that within the Josephson superlattice model (JSM) the *SW* of the t-JPR belongs to the SC condensate just as much as the one of the δ-function at zero frequency.

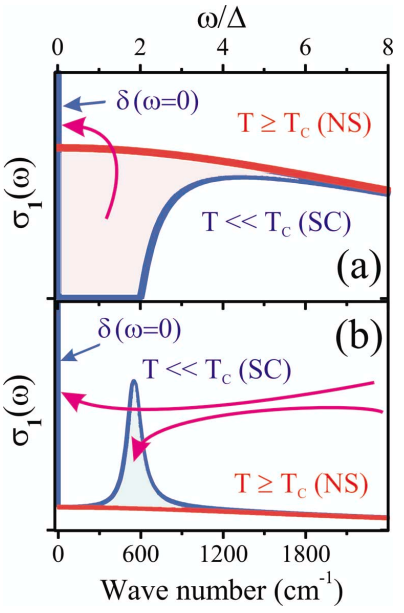

Figure 2. *(a) Sketch of the SC induced change of the FIR conductivity (a) for classical materials with a s-wave SC order parameter. (b) as observed in Bi2223.*

It is evident from **Figure 1** that the formation of the t-JPR is also associated with an anomalous temperature dependence of the phonon modes. Particularly interesting are the contrasting *T* dependences of the modes at 360 and 400 cm^{-1}. As shown in **Figure 3a**, the mode at 360 cm^{-1} loses a significant amount of its SW below T_c, while, in clear contrast, the latter one gains in the *SW.* Both phonons are assigned to be oxygen bond-bending modes with the eigenvector diagrams shown in **Figure 3b**. Their contrasting behavior, while surprising at first, is explained by the JSM. A sketch of the charge dynamics corresponding to the t-JPR is shown in **Figure 3c** where κ(ω) denotes the charge density that alternates from one outer plane to the other. The onset of the Josephson currents j_1 and j_2 between the CuO_2 layers below T_c can lead to a significant change of the dynamical local electric field inside the the trilayer, E_1, inside the spacing layer that separates the trilayers, E_2, and at the outer CuO_2 layers, E_3. The strength of a given phonon mode is determined by the local field at the ions participating in the mode and by the mode polarizability. The main difference between the oxygen bond-bending modes is in relative phase and amplitude of the inner and outer-plane oxygen vibrations: The mode at 360 cm^{-1} consists predominantly in the vibration of the oxygens in the outer CuO_2 planes (O1), the latter one involves vibrations of the oxygens in the middle CuO_2 (O4) plane. Following the simple model being discussed here, we estimate that the average magnitude of E_3 at O1 ion sites is strongly suppressed below T_c, while the magnitude of E_1 inside the trilayer at O4 sites increases. The local field effect leads to the observed contrasting behavior of the oxygen bond-bending modes in the SC state. These phonon anomalies clearly reflect a transition from a state exhibiting confinement (incoherent intra-trilayer conductivity) into a state where the CuO_2 planes are Josephson coupled. They demonstrate that, in the SC state, the local electric field can exhibit enormous variations within the unit cell.

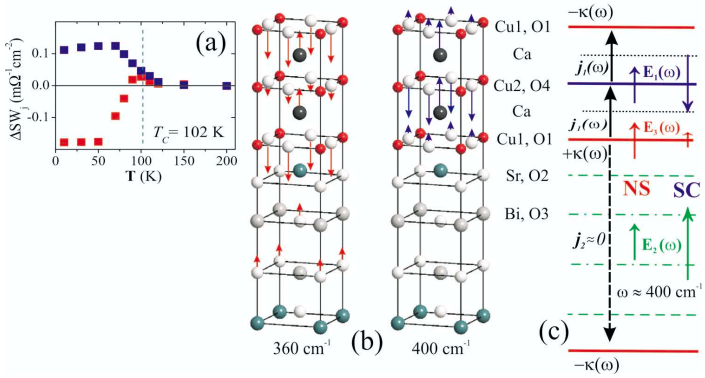

Figure 3. *(a) Relative* SW *changes of the phonons at 360 cm^{-1} (red squares) and 400 cm^{-1} (blue squares) with decreasing temperature. (a) Calculated oxygen bond-bending A_{2u} eigenmodes of Bi2223. (c) Schematic representation of the charge density fluctuations associated with the IR active plasma mode and the related local electrical field in the normal and SC states in the frequency range of the bond-bending modes.*